国际工程期刊
International Journal of Engineering Works
انجینرنگ کاموں کا بین الاقوامی جرنل

International Journal of Engineering Works
ISSN-p: 2521-2419
ISSN-e: 2409-2770
Vol. 5, Issue 10, PP. 216-223, October 2018
https://www.ijew.io/

APU Gas Turbine Perforemance Monitoring and Fault Diagnosis in Aircraft System based on QAR

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Received: 02 July, Revised: 15 October, Accepted: 27 October

Abstract—The aircraft complex systems (ACS) contains the auxiliary power unit (APU) based gas turbine, the performance assessment is totally cramped to inspection of different kind of parameters. So many other parameters can be observed in Quick Access Recorder (QAR) returns the APU condition from different aspects not having enough attention. The investigation intends to propose incorporated performance indicators by feature extraction many observing parameters. To approve the effectiveness of the strategy by anomaly identification, the clustering analysis is conducted. This technique can possibly effectively evaluate performance of some complex aircraft systems for early cautioning and prevent degradation at early stage. The parameters of Rowen's model for APU based gas turbines in unique studies are assessed by utilization of accessible operational and performance data. Here, the work is planned to make understanding into different parts of the APU model and to present simple and comprehensive strategy to extract the parameters out of basic physical laws, focusing especially on researchers to let their interest in dynamic models and simulations. Gas turbine parameters are approximated by using straightforward thermodynamic assumptions, resulting great performance. In this paper, the step response of the simulation model is also simulated for number of scenarios and is presented here.

Keyword: Air-Craft, APU, Gas Turbine, Dynamic simulation, gas turbine, mathematical model, thermodynamic process.

I. Introduction

Aircraft systems are complicated system. In the design stage and in the operating process to ensure continued air quality of the aircraft. It is broken down into simpler sub systems that carry out homogeneous functions. There are two types of power supply use in the aircraft system to work, first is main power unit and second is auxiliary power unit. APU works during the phases when the aircraft's main engines are shut down and to support the electrical and air conditioning systems. Auxiliary Power Unit (APU) is one of complex electromechanical systems in aircraft which serves as a small engine. It is mainly used to provide compressed air and electrical power on ground and used as alternative power supply in air in case of emergency. A typical APU system for commercial aircraft consists of three main sections, the load compressor that provides all pneumatic power, the power section which is a gas generator supplying all power and the gearbox which transfers power. Another two important devices are the inlet guide vanes and the surge control valve, which are used to regulate airflow into the load compressor and maintain turbo machine stable separately. It is typically installed in the aircraft tail cone and the primary function is to provide power to start the main engines and provide energy for functions other than propulsion. APUs can also be used to run accessories like air conditioning system in the cabin while the passengers are boarding before the aircraft engines are started. In normal operation.

A typical APU for commercial transport aircraft is broken up into three main sections –

(1) the power section,
(2) the load compressor
(3) the gearbox.

The power section is the gas generator portion of the engine and produces all the power for the APU. The load compressor is generally a shaft-mounted compressor that provides all pneumatic power for the aircraft. Auxiliary power unit (APU) is standard equipment on today's civil aircraft. It is a small gas turbine engine that makes the aircraft independent of ground power supplies. GAS turbines are one of the fundamental sources for power generation in nations with flammable gas assets and are introduced in various places in globe because of their uncommon qualities. A mathematical representation of gas turbines of power system analyst needs dynamic studies to have a several journals [1]–[3]. A standout amongst the most normally utilized improved models was exhibited by Rowen [1] considering the load-frequency and temperature control and in addition the turbine's thermodynamic reactions as a straight capacity and delta direct vane impacts in a different work [2]. A few models with various degrees of improvement for the representation of gas turbines in dynamic studies were presented, among which the IEEE demonstrate for joined cycle power plants had further sight into internal processes [3]. A review of the models is given in [4].

II. Gas Turbine APU

Gas turbines are engines within which the chemical energy of the fuel is converted either into mechanical energy in terms of shaft power or into kinetic energy. Gas turbines that produce shaft power are power generation gas turbines. Gas turbines that convert the fuel energy into kinetic energy are used for generation of thrust to propel an aircraft. The conversion of fuel energy into shaft power or propulsive force, requires interaction of several components of the engine, within each of them a chain of energy conversion takes place.

Types of gas turbine

- Turboprop engines
- Jet engines
- Aeroderivative gas turbines
- Amateur gas turbines
- Auxiliary power units
- Industrial gas turbines for power generation
- Industrial gas turbines for mechanical drive
- Turboshaft engines
- Radial gas turbines
- Scale jet engines
- Microturbines

Application Area of gas turbine

- Gas turbine plants are used as standby plants for the hydroelectric power plants.
- **Gas turbine power plants** may be used as peak loads plant and standby plants for smaller power units.
- Gas turbines are used in jet aircraft and ships. Pulverised fuel-fired plants are used in a locomotive.

APU Gas Turbine (APUGT) are exceptionally designed gas turbines for power generation which are determined by their long life and higher accessibility thought about different kinds of gas turbines. AGTs are made out of three major segments: multistage axial stream compressors, can-annular combustors and pivotal stream turbines. Fig. 1 demonstrates an ordinary AGT with its segments. Air with climatic conditions is attracted to the compressor subsequent to passing air channels at the passage. The multi stage compressor expands speed, weight and temperature of the air before it comes to the combustor and bay to the high weight turbine parts. Every compressor arranges contains a rowe of rotor cutting blades and stator vanes. Of significance is a column of stator vanes at the inlet (variable inlet guide vanes, VIGVs) whose angle might be changed by the control system during activity. As shown in Fig. 1, the packed compressed air with high pressure and temperature will pursue its way to the combustor. The combustor is fundamentally a heater in which fuel is scorched to increase the temperature at constant pressure.

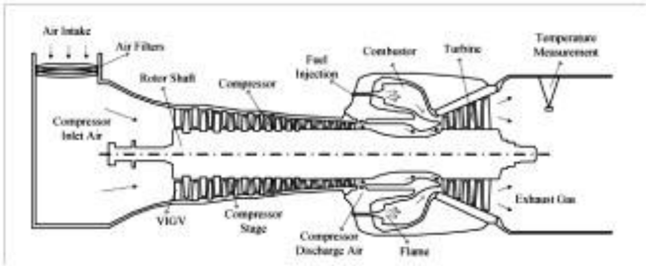

Figure 1. Schematic view of a typical AGT and its major components.

Roughly one third of the compressor discharge air is mixed with the fuel to be burnt, while the remaining air is mixed with combustion products to become the turbine inlet flow which is now at turbine inlet temperature (TIT) [7]. The flow is then expanded in 2–4 turbine stages which drive compressor and generator. Finally, the flow is guided through the exhaust duct to a second environment which can be surrounding ambient conditions or a heat recovery steam generator (HRSG) in combined cycle plants (CCP). In addition to air/gas dynamics passing through major components of the gas turbine, there are other equipments which are of interest in the gas turbine model like exhaust gas thermocouple and its radiation shield and the fuel valve system and valve positioner. An estimation of these equipment parameters is done as well. The gas turbines work with the Brayton cycle. Fig. 2 shows a typical standard Brayton cycle in temperature-entropy frame.

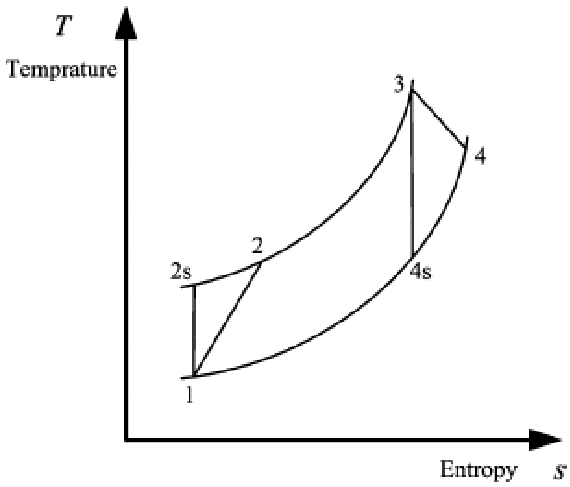

Figure 2. Typical Brayton cycle in temperature-entropy frame.

Air is drawn from point 1 in surrounding condition and is compressed by the compressor in an irreversible procedure to point 2. Input value of heat in the combustor will build the temperature to point 3 where the combustion product and compressor release air will enter the turbine and grow to point 4. In this figure, the pressure loss in the air filters and the combustion chamber is ignored, i.e., the procedures 2-3 and 4-1 are thought to be isobar.

The procedures in the compressors and turbines are irreversible and non-isentropic; be that as it may, in Fig. 2 the expected isentropic procedures are shown as well. These perfect procedures would be utilized to characterize the compressor and turbine irreversible adiabatic efficiency as pursues:

$$\eta_c = \frac{h_{2s}-h_1}{h_2-h_1} \approx \frac{T_{2s}-T_1}{T_2-T_1} \quad (1)$$

$$\eta_t = \frac{h_3-h_4}{h_3-h_{4s}} \approx \frac{T_3-T_4}{T_3-T_{4s}} \quad (2)$$

Where h stands for the fluid mixture enthalpy (kJ/kg) and is the absolute temperature in K. The subscript s indicates the isentropic process. In operation, the turbine's efficiency η_t is more affected by changes in load and speed than compressor efficiency η_c is [7]. This is mainly because the compressor is operated in relatively constant thermodynamic conditions but the turbine condition greatly varies. In deriving the gas turbine model parameters, the above efficiencies are used and assumed constant in a limited range of operational conditions where the turbine response can be approximated to be linear [1], [3]. Therefore, in the next sections operational data are first used to derive the above efficiencies to extract turbine parameters.

III. APUGT Model for Stability Analysis

The mathematical representation of an APUGT in dynamic studies by Rowen's model is shown in Fig. 3. There are two major controls which are shown in this figure. These are load frequency and temperature control (originally, in [1] acceleration control have been shown and in [2] inlet guide vanes (IGVs) have been modeled which are not included here). Variable IGV (VIGV) are to regulate the air mass flow drawn into the compressor. Actually the VIGV are in operation in CCP applications where they regulate the air flow to maintain the efficiency of gas turbine during operation at partial load. The VIGV control is mainly affected by exhaust gas temperature. If this temperature is below the reference (near to rated temperature) then VIGV will open and, in fact, it will become fully opened in normal operation of around nominal power. Nevertheless, in partial load and start up, the exhaust temperature is not that high and the VIGV are partly closed. In simple cycle operation, VIGV control is only active during start up. In this paper, we do not consider the VIGV and acceleration control as the model is to be tuned around nominal operation and VIGV are considered fully open. The fuel demand signal is the minimum value of temperature and load-frequency control. The sequence of model blocks is: fuel demand limitation, no load consumption, valve positioned and fuel system dynamic, volume discharge delays, turbine model (for output torque and temperature), temperature measurement system [1]. Apart from the control set-points, other parameters of the models are based on physical behavior of the HDGT's components.

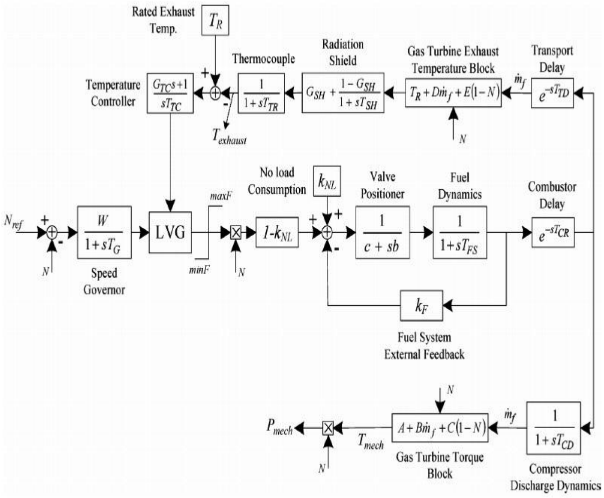

Figure 3. Rowen's model for APUGTs for dynamic studies [1].

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A. Turbine Parameters

In the APUGT model of Fig. 3, the turbine behavior is reflected by two quantities. First, the output torque and second the exhaust gas temperature. To see the turbine parameters in more details, let us start with Fig. 2 and efficiencies of compressor and turbine. In the isentropic process of 1–2s, we have [9]

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_c-1}{\gamma_h}} = PR^{\frac{\gamma_c-1}{\gamma_c}} = x_c \quad (3)$$

$$\frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma_c-1}{\gamma_h}} = PR^{\frac{\gamma_c-1}{\gamma_c}} = x_h \quad (4)$$

where $P_2/P_1 = P_3/P_4 = PR$ (pressure drop in combustor is neglected) is the cycle pressure ratio. γ_c and γ_h are the cold end (compressor) and hot end (combustor, turbine) ratio of specific heats, respectively. The variable x is defined to make referencing simpler in the next equations. Generally $\gamma =$

C_p / C_v where C_p is the specific heat of air at constant pressure and is the specific heat at constant volume.

It is important to know that C_v the specific heats and ratio vary with temperature. One common approach is to use the hot end and cold end air properties as follows [10]:

C_{ph} = 1.1569 kJ/kgK and γ_h=1.33 (5)

C_{pc} = 1.0047 kJ/kgK and γ_c=1.4 (6)

Using (1) and (3), temperature after the compressor is computed as follows:

$$T_2 = T_1\left(\frac{x_c - 1}{\eta_c} + 1\right) \quad (7)$$

and with (2) and (4), we get

$$T_4 = T_3\left[1 - \left(1 - \frac{1}{x_h}\right)\eta_t\right] \quad (7)$$

Another process which affects the APUGT's behavior is the process which takes place in the combustor, i.e., 2–3 in Fig. 2. A constant pressure process in the combustor will lead to the following expressions:

$$\dot{q}_H = \dot{m} \cdot c_{ph} \cdot (T_3 - T_2) \quad (9)$$

where $\dot{m}$ (kg/s) is the air flow rate. The heat is produced by extracting energy from the fuel as follows:

$$\dot{q}_H = \eta_{comb} \cdot \dot{m}_f \cdot H \quad (10)$$

where $\dot{q}_H$ (kJ/s) is the heat absorption rate in the combustor, is the combustor efficiency, $\dot{m}_f$ (kg/s) is the fuel flow rate and (kJ/kg) is the lower calorific or lower heating value of fuel in use. The combustor efficiency stands for the portion of fuel that is injected into the combustor but is not burnt. For state of the art designs, combustor efficiency is very high and near to unity. Using (9) and (10) the temperature rise in the combustor can be computed as follows:

$$T_3 = T_2 + \eta_{comb}\frac{\dot{m}_f}{\dot{m}}\frac{H}{C_{ph}}T_2 + \Delta T_0\frac{\dot{m}_f}{\dot{m}} \quad (11)$$

ΔT_0 is a simplifying symbol of a temperature rise coefficient. Actually, the internal temperatures and pressure ratio and overall response of APUGT vary with speed. These responses are nonlinear and further complicate the models. However, in Rowen's model, a linear model is assumed with respect to speed by applying the speed constraint of 95% to 107% of nominal speed; see Fig. 3. We also will assume a linear response with respect to speed deviations, but first let us assume our APUGT at nominal speed. In this point, the per unit output torque and mechanical power would be the same. Then

$$P_G = \dot{m} \cdot [C_{ph}\,(T_3 - T_4) - C_{pc}\,(T_2 - T_1)] \quad (12)$$

By simple mathematics, the above equation is written in the form of the power block in Fig. 3 using (7), (8), and (11), i.e.

$$P_{Gpu} = A + B \cdot \dot{m}_{fpu} \; at\ nominal\ speed \quad (13)$$

$$A = \frac{\dot{m}_n \cdot T_1}{P_{Gn}}\left\{\begin{array}{c} C_{ph} \cdot \eta_t \cdot \left(1 - \frac{1}{x_h}\right) - \frac{x_c - 1}{\eta_c} \\ \times\left[C_{pc} - C_{ph} \cdot \eta_t \cdot \left(1 - \frac{1}{x_h}\right)\right] \end{array}\right\} \quad (14)$$

$$B = \frac{\eta_{comb} \cdot \eta_t \cdot H \cdot \dot{m}_{fn}}{P_{Gn}}\left(1 - \frac{1}{x_h}\right) \quad (15)$$

where A and B are the coefficients of output torque in Fig. 3; $\dot{m}_m$ and $\dot{m}_{fn}$ are the air and fuel nominal flow rates; and P_{Gpu} is the per unit output power which is equal to the p.u. torque. It should be stated here that the turbine nominal power is the base of p.u. for [13]–[15]. At nominal speed, the exhaust temperature can be computed by substituting (11) and (7) in (8). Therefore

$$T_4 = T_R - D \cdot (1 - \dot{m}_{fpu}) \text{ at nominal speed} \quad (16)$$

$$D = \eta_{comb}\frac{H}{C_{ph}}\frac{\dot{m}_{fn}}{\dot{m}_n}\left[1 - \left(1 - \frac{1}{x_h}\right)\eta_t\right] \quad (17)$$

Where D is the coefficient of the exhaust temperature block in Fig. 3 and T_R is the nominal exhaust temperature of the APUGT. To extract the parameters, a typical operational condition is selected to derive the turbine and compressor efficiencies and then all above parameters are computed with available data out of unit operation

$$T_{Gpu} = \frac{k+1}{k} - \frac{1}{k}N_{pu} \quad (18)$$

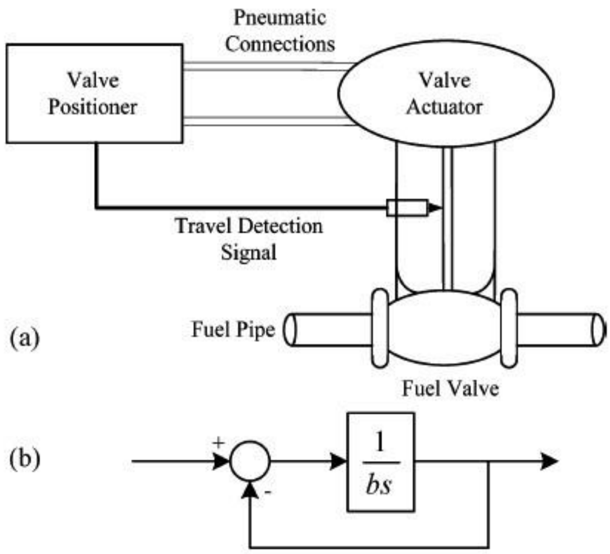

Figure 4. Pneumatic valve positioner and valve actuator.
(a) Schematic view.
(b) Internal feedback mathematical model.

where k is a constant and depends mainly on the thermodynamic cycle design and frictions. It is a tedious job to go through the details of this parameter [9]. Fortunately, the design constraints for APUGTs do not allow high variations in and values of 1.5 to 2 are common. Therefore, C'=1/k in power block of Fig. 3 varies between 0.5 and 0.67. Note that all above concepts are only valid when we are in the linear area of the turbine response with respect to speed deviations. The same approach regarding temperature changes versus speed will make the coefficient E in exhaust temperature block of Fig. 3 to vary in the range of 0.55 to 0.65 of rated exhaust temperature. The fact that HDGTs need relatively high fuel consumption to operate even in no load conditions is reflected in Rowen's model by dividing the fuel demand signal to positioner system into a constant part (constant kNL in Fig. 3) and the reducing gain multiplied by the demand signal (block 1- kNL in Fig. 3). kNL can be extracted from available operational data.

There is also a fuel demand signal limiter in the APUGT model of Fig. 3. The maximum extent of the limiter is not reached in normal operation and may act as a backup to temperature control where any increase in turbine exhaust temperature will lead to activation of temperature control and decreasing fuel flow [1]. Anyway, the minimum extent is a negative value which shows the gas turbine ability of transient power absorption. Its value depends on minimum fuel flow required to maintain the flame in combustor. A value of 1.5 p.u. is commonly used for maximum extent while minimum value can be determined by available fuel system data.

B. *Valve Positioner and Fuel System Lag*

The valve positioner moves the actuator to a valve position corresponding to the set point. In Fig. 4, the valve positioned and its connection to the valve actuator and valve system is presented. Due to the fact that APUGTs are able to operate with liquid and gas fuel, the fuel system models are essentially two different systems with similar blocks. In larger APUGTs both fuel systems are supplied with inner loop feedback which senses the current position of the valve and eliminates the error between set point and position signal, see Fig. 4. Therefore, only one time constant will appear, which is in the valve positioner block of Fig. 3. The positioner time constant can be found in the manufacturer data or similar available data for older units. Moreover, in liquid fuel systems, there is a bypass way from the fuel pump output to the pump section. Bypass path is presented in Rowen's model by the feedback loop gain. The value of is explicitly calculated to force the overall valve positioner-fuel system loop gain to unity [1].

As a result, the product of and (valve positioner block in Fig. 3) should become zero, i.e., the value is zero for our large APUGTs if is not. Note that this is not always the case, especially when inner loop feedback does not exist, see [1] for more details. Assuming linear response actuators and valves, the fuel flow will change directly with the output signal of the valve positioner. However, there is a lag associated with gas/oil flow in the pipes and fuel system manifold. This lag can be approximated by the following expression[8]:

$$T_V = \frac{P_0}{Q_0} V \frac{\partial}{\partial P}\left(\frac{1}{v}\right)_{T_0} \qquad (19)$$

where in s is the time constant of the lag associated with the container of volume in , is the average pressure in Pa (kg/m.sec2), is the steady state mass flow out of the container in kg/sec and $\partial(1/\mathrm{v})\ \partial$P(sec2/m2)is the density change due to pressure changes at constant temperature where is the specific volume. For gas fuels, the lag constant is considerably higher due to higher changes in the specific volume. Knowing the rough estimates of parameters in [17] makes it possible to obtain rough values for the lag time constant; see Section IV.

C. *Time Delays and Discharge Lag*

The gas turbine behavior forces its dynamic model to have small delays and lag time constants. Actually there is a small time delay between the fuel injection and heat release in the combustor which is called combustion reaction delay. In modern systems it is on the order of some ms [10]. This time delay is implemented in Rowen's model as a time delay after the valve systems. There is also a time delay between the fuel combustion and exhaust temperature measuring system. This delay is caused by the exhaust system and turbine to transport the fluid to the measuring point; see Fig. 1, and is in the order of some 10 ms depending mainly on the size of the APUGT and the average fluid speed. A relatively higher time lag exists in the compressor discharge path to the turbine inlet. It can also be approximated by [17].

D. *Temperature Measurement*

Temperature control in APUGTs requires measurement of the exhaust temperatures which may be composed of thermocouple and radiation shield [1]. Generally, there are three ways of heat transfer between materials: conduction, convection and radiation. Here, we are only interested in the exhaust gas temperature out of the turbine (a convective source) to control the temperature and avoid excessive heating. Nevertheless, the radiation source, i.e., the turbine itself, will cause errors in the temperature measurement. The radiation shield is therefore used to overcome the problem. The radiation shield is a polished, highly reflective metal shield that is placed around the thermocouple and reflects most of the radiation away from the thermocouple and itself;

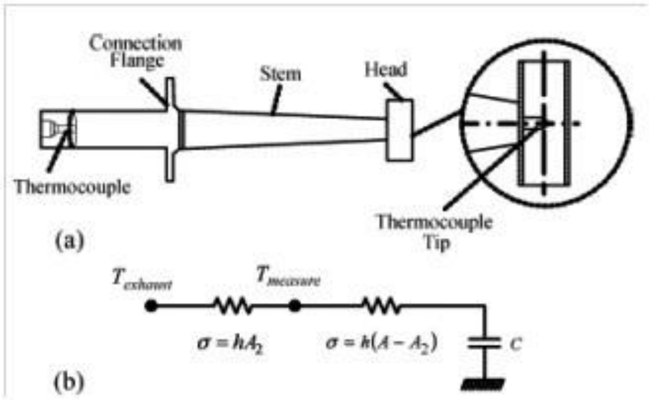

Figure 5. Radiation shield and thermocouple.

(a) Schematic of radiation shield and mounted thermocouple. (b) Simplified equivalent electric circuit for calculating the temperature at thermocouple position. see Fig. 5. This equipment will cause a lag based on its heat transfer behavior to be presented in the model. Let us assume a simple model of the heat transfer paths of Fig. 5. The temperature at the thermocouple tip will then be approximated by

$$\frac{T_{measure}}{T_{exhaust}} \approx \frac{A_2}{A_1} + \frac{1-\frac{A_2}{A_1}}{\frac{C}{hA_1}s+1} \qquad (20)$$

where A_1 is the total active area for convection heat transfer to the shield head, A_2 is the area effective for convection heat transfer to the thermocouple tip,C (J/K) is the heat capacity of the shield head and h (W/m2K) is the convection heat transfer coefficient [11]. Temperature measurement device is the thermocouple which has a typical lag with a time constant based on its type and design. Time constant of thermocouple can be easily extracted from its time response documents.

IV. RESULT AND DISCUSSION

The complete system is designed and simulated in Matlab/Simulink. The Simulation is done for 50 seconds as shown in the figure 6.

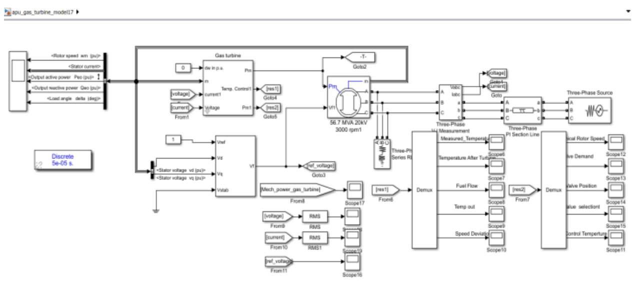

Figure 6. Simulation mode

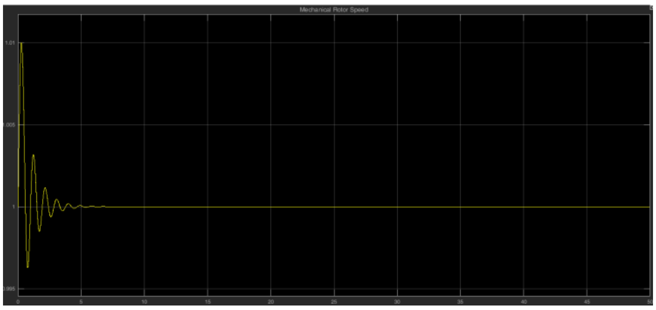

Figure 7. Mechanical Rotor Speed

In figure 7, the variation of mechanical rotor speed w.r.t time is shown. It varies initially and becomes stable at 8 sec.

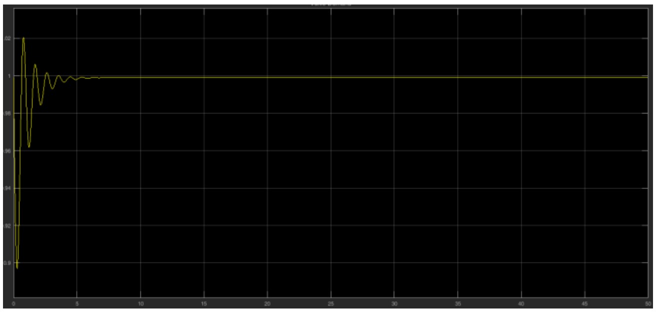

Figure 8. Valve Demand

In figure 8, the variation of valve demand w.r.t. time is shown. It varies initially and becomes stable at 8 sec.

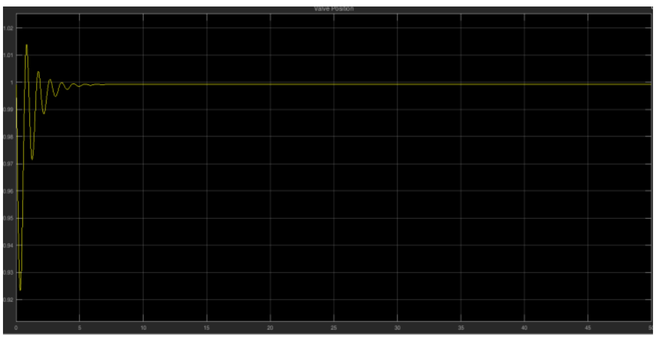

Figure 9. Valve Position

In figure 9, the variation of valve position w.r.t. time is shown. It varies initially and becomes stable at 8 sec.

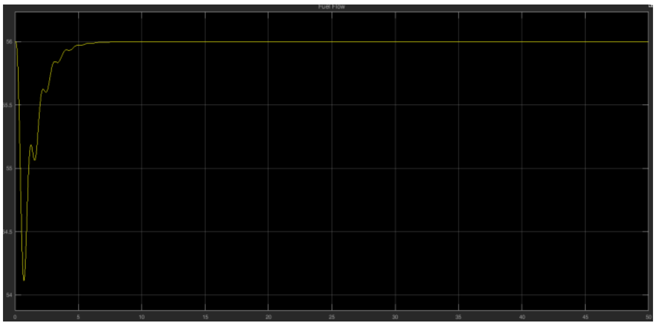

Figure 10. Fuel Flow

In figure 10, the variation of fuel flow w.r.t time is shown. It varies initially and becomes stable to 56 at 8 sec.

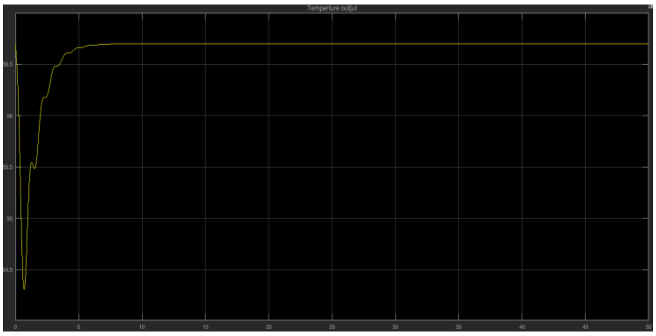

Figure 11. Temperature Output

In figure 11, the variation of temperature output w.r.t time is shown. It varies initially and becomes stable to 56.7 at 8 sec.

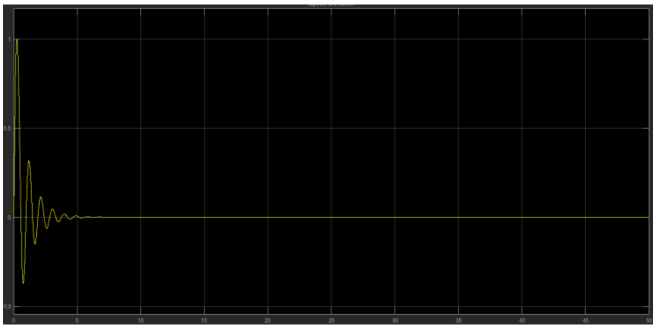

Figure 12. Speed Deviation

In figure 12, the variation of Speed Deviation w.r.t time is shown. It varies initially and becomes to 0 at 8 sec.

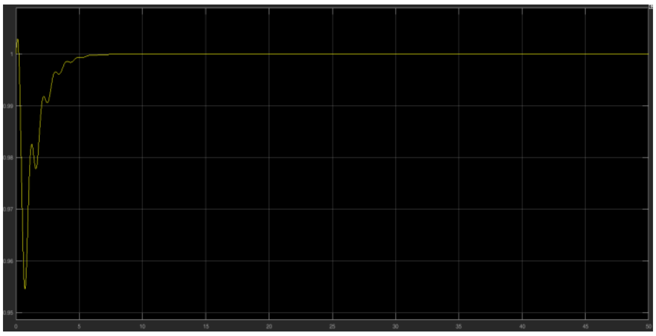

Figure 13. Mechanical Power Gas Turbine

In figure 13, the variation of mechanical power gas turbine w.r.t. time is shown. It varies initially and becomes stable at 8 sec.

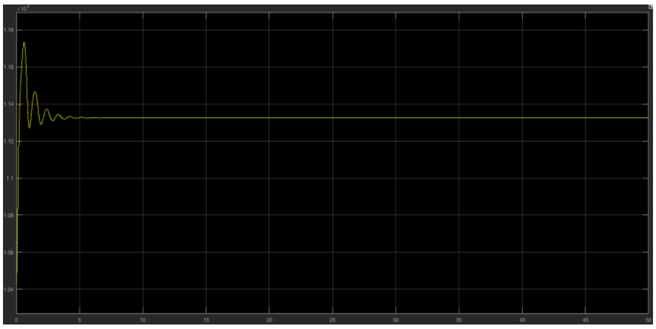

Figure 14. RMS Voltage

In figure 14, the variation of RMS voltage w.r.t. time is shown. It varies initially and becomes stable at 8 sec.

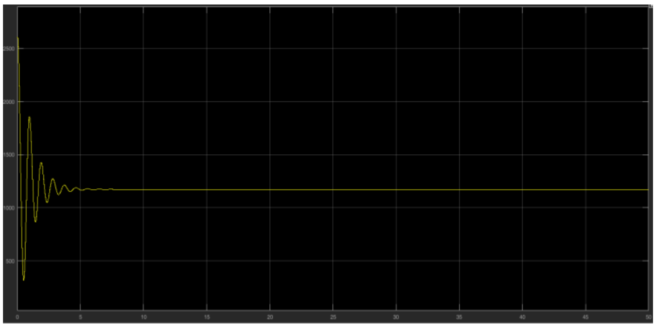

Figure 15. RMS Current

In figure 15, the variation of RMS current w.r.t. time is shown. It varies initially and becomes stable at 8 sec.

Figure 16. Multiple Value Comparison

In figure 16, the variation of rotor speed (p.u.), stator current, active power (p.u.), reactive power (p.u.), load angle w.r.t. time is shown. Initially all values varies and becomes stable at 8 sec.

CONCLUSION

The research paper is described three progressively propelled techniques to demonstrate the diagnostics of aircraft auxiliary power units (APU). The increasing multifaceted of the methodologies corresponds to the increasing trouble handling them with the legacy engines. It has been shown that a reliable diagnostics of faults is possible even by rarely data collected on such engines. This is accomplished with the use of high fidelity models of the available engine. In view of dependability analysis & forecast, high danger of APU gas turbine's can be scheduled off. The unused APU gas turbine can be set up in advance. Shop repair, investigating and maintenance activities can be better arranged. APU based gas turbine safety & accessibility can be essentially improved, so that operating & maintenance cost can be minimized. The risk of APU based gas turbine APU failures can be observed an aircraft fleet and not for single system. The investigative result can be used by unwavering quality experts and the people managing system. In this paper, a basic technique is shown for evaluating the parameters of Rowen's model. It is described in detail how to extract the model parameters by operational datasets.

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